VISUAL PERFORMANCE AND LIGHT SPECTRUM: THE INADEQUACY OF CONVENTIONAL PHOTOMETRY

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ABSTRACT

At light levels typical of building interiors it is the optical quality of the eye rather than retinal illumination that limits visual acuity and contrast sensitivity. Because aberrations generally occur in the eyes of the majority of the population and because smaller pupils reduce the defocusing effects of aberrations, pupil size becomes the major factor that light spectrum can control to influence visual performance. Our studies demonstrate that for conditions of full field of view and light levels typical of interior spaces, pupil size as measured by objective infrared pupilometry, is predominantly controlled by scotopic spectrum. We also demonstrate in a series of 10 separate studies with different subjects that pupil size is the ultimate factor in limiting acuity and contrast sensitivity at typical interior light levels. A large number of subjects are employed in these studies which take place under conditions of binocular viewing in a 2 m cubic room lit by a variety of fluorescent lamps.

1. INTRODUCTION

Illumination recommendations for building interiors are often based on visual performance which is generally considered an important design criterion. Furthermore, such illumination recommendations are universally prescribed in terms of photopic lux (or foot candles in North America). The use of photopic units as the measure of light quantity applied to visual performance is usually justified by a number of studies which indicate V(λ)-like spectral responses to stimuli of high spatial and temporal frequency content.[1] However, these studies that produce the V(λ) function are universally confined to measurements utilizing small fields of view, typically 2° of visual field and occasionally 10° of visual field. Even measurements which include the Judd correction[2] and other procedures involving heterochromatic brightness matching are confined to small fields.[3] Lighting practice for building interiors is hardly ever confined to such small fields of view and lighting designers have complained for decades that V(λ) based photometry appears inadequate and often contrary to many of their observations. Our studies reviewed here demonstrate that visual sensitivity is indeed quite different in full field viewing. They also provide a scientific basis for many of the observations made by generations of successful lighting practitioners. These studies show under conditions of full field of view and at light levels typical of building interiors that rod photoreceptors are active causing additional spectral sensitivity. In particular, we demonstrate that, pupil size is predominantly controlled by the scotopic response, that pupil size is more important than retinal illumination in determining visual performance and that brightness perception has both scotopic and photopic responses. We review here our determination of the spectral determinants of pupil size and also several of our studies that show the importance of pupil size as the ultimate determinant of visual performance at typical interior lighting conditions.

2. THE SPECTRAL RESPONSE OF STEADY STATE PUPIL SIZE

In 1934 Luckiesch and Moss[4] made an observation by direct visual inspection comparing an eye under incandescent and low pressure sodium lighting of equal illumination. They observed that the pupil appeared much larger under the LPS lighting than under the incandescent lighting. Almost 30 years later, Bouma[5] used the method of subjective entoptic pupilometry and claimed a pupillary spectral response that was totally scotopic over the entire range of luminances which yield pupil size changes. A few years later Alpern and Campbell[6] applied an objective measurement method based on infrared photography to demonstrate that if the field of view is confined to a few degrees, the consensual pupil spectral response was entirely photopic and that at their largest field of view, about 20°, it was an equal mixture of photopic and scotopic response. During the next two decades other vision scientists claimed various results (see Hedin)[7] and some claimed that the steady state or tonic pupil response was entirely photopic, i.e., Alexandridis.[8] In spite of the results of Bouma and Alpern and Campbell,[5,6] the possibility that visual sensitivity might not be governed by the V(λ) function alone does not appear to have penetrated into the field of illumination engineering.

In order to bring the relevance of scotopic sensitivity to the attention of lighting practice, we have undertaken and are continuing a series of systematic investigations under experimental conditions more closely related to realistic interior environments.

The first phase of this effort used the following principle protocols for the determination of the spectral response of the pupil:

i) Many subjects are employed allowing the results to be related to the standard photopic and scotopic observer.

ii) Subjects are comfortably seated in a room (2m x 2m x 2m in size) and view a fixation point binocularly. The room surfaces are predominantly white with the walls and ceiling painted with spectrally uniform paint. Room luminance is approximately uniform and vertical illuminance at the eye of subjects is proportional to the luminance at point of view.

iii) Pupil size measurements of subjects' right eye are accomplished using computerized and automated infrared pupilometry enabling thousands of datum to be gathered. Due consideration has been given to assure that any IR emissions from the test lighting does not affect the pupilometer.

iv) Lighting is provided indirectly by fluorescent lamps and spectral variation is accomplished by using a wide variety of phosphors. Both lamp and wall reflected spectral power distributions (SPD) have been measured using a Pritchard spectrophotometer scanning at 1 nm intervals. Photopic and scotopic luminances are determined by folding the measured lamp SPD against standard observer functions[9]. Lamp luminance control was provided by high frequency electronic dimming ballasts. Dimming the lamps produced no measurable effect on the SPD. The direct lamp luminances and the wall luminances derived from the SPD agreed within 2%, which is the measurement error of the measured wall reflected SPD whose values were very small at the tails of the photopic and scotopic standard observer functions. Luminance was roughly constant in the field of view varying about 15% from central to far side.

v) Pupilometer calibration was accomplished with artificial pupils and was repeated on a regular basis.

vi) The pupilometer apparatus did obscure a portion of the visible field of about 1.06 steradians out of a total field of view of 6.24 steradians. The binocular field of the walls providing just a single bounce of indirect lighting was about 4.95 steradians.

vii) A subject fixation point for the measurements was located 1/2 m above the floor and 1.25 m from the left wall and about 1.1 m from the subjects eyes. Subjects were adapted to each lighting condition for 2 minutes before pupil measurements commenced.

viii) Subjects ages ranged from 21 to 46 years.

A number of pilot studies were undertaken before the main study was carried out. The main studies involved 32 subjects and two different viewing protocols.

Since the object of the study was to determine the relative contributions of scotopic and photopic spectrum to pupil size in full field of view, we used a variety of different fluorescent lamps having a wide range of the ratio S/P (S and P are the scotopic and photopic luminances whose values are derived from the measured spectral power distributions of the lamps). Six different lamps were employed with S/P values ranging from 0.58 to 4.31. Photopic luminances as measured on the viewing wall ranged from 20 to 275 cd/m^2. As mentioned above, subjects were adapted to each condition for at least 2 minutes before measurements began.

Pupil area was sampled by the pupilometer at a rate of 20 Hz over a 20 second recording epoch. The various lamps and luminances were presented in random order with a different random order for each subject. The conditions were repeated between 3 and 5 times for each subject.

After blink removal the data was log transformed (our analyses showed log transformed data led to the highest degree of accountable variance). To account for the naturally occurring individual differences in pupil size between subjects we subtracted each subjects mean pupil area from all that subjects data. Averaging over the subject pool showed a very good fit to straight line functions of log area versus log luminance for each lamp. Quadratic and cubic additions were not statistically significant.[1] Figure 1 shows the average ln (natural logarithm) area plotted against ln photopic luminance. The different lamps with their different SPDs are parallel but shifted indicating the strong statistical interaction between scotopic and photopic luminance. The graph shows the trend that higher photopic luminances produce smaller pupils, but photopic luminance is a very poor predictor of the data.

The same data is then further analyzed assuming a form:

$$\text{log pupil area} = \text{c-a log s - b log P} \qquad (1)$$

(a, b, c are constants independent of lamp and luminance) or equivalently

$$\left(\frac{A}{A_o}\right) = \left(\frac{S_o}{P_o}\right)^a \left[\left(\frac{P}{P_o}\right)\left(\frac{S}{P}\right)^{\frac{a}{a+b}}\right]^{-(a+b)} \qquad (2)$$

where P_o and S_o are the luminances at some reference pupil area A_o (within the range where the linear logarithmic character is appropriate).

The exponent (a/a+b) is determined by analyzing the data of each subject using eq. (1). Subsequent averaging over subjects and conditions leads to a value 0.78 ± (.03 s.e.) for the exponent.

Figure 2 shows the same data as Figure 1 with the abscissa determined by this statistically fit as:

$$P\,(S/P)^{0.78} = \text{Pupil luminance.} \qquad (3)$$

The data is fit very well with this empirically determined value of pupil luminance which accounts for about 80% of the within subject variance (WSV = Total Variance - Between Subject Variance). The right side of Figure 2 shows both the WSV indicated as A and the sum of WSV and BSV indicated as B.

We note that these results are consistent with the results of Alpern and Campbell,[6] but not with the compilation of de Grout and Gebhard.[10] The latter authors failed to take into account that light sources of differing spectral power distributions and hence, difference S/P values, contributed to the data. Further discussion and more detailed descriptions can be found in Berman et al.[11]

3. VISUAL PERFORMANCE WITH PUPIL SIZE CONTROL

Having demonstrated the dominance of scotopic spectrum for determining pupil size, we now turn to a series of studies that demonstrate the importance of pupil size as an underlying mechanism in limiting visual performance. In these studies we show that when task luminances range over values typical of building interiors, pupil size is more important in affecting visual performance than retinal illuminance. The basic reason why this occurs is that aberrations in the optical system of the eye affect its optical quality much more than the improvements related to increased retinal illumination. Making the pupil smaller reduces the defocusing effects of these aberrations and thus, when the retina is not "photon starved", i.e., at typical interior illuminance, retinal image sharpness is improved with a smaller pupil. Recent studies by Colleta et al[12] have shown that when the eyes optical system is essentially bypassed by applying laser interferometry, retinal acuity is almost constant and reaches its maximum for luminances about 1 cd/m^2. Thus, at the levels of interior lighting retinal resolution is less likely to be dependent on light quantity with image quality more likely to be determined by the dioptrics of the eye.

[1] We examined polynomial fits to both the independent and dependent variables, and of log transformations of either, or both. The data were analyzed using the General Linear Models (GLM) procedure of the Statistical Analysis System. All analyses and model testing were performed using the GLM linear regression procedures for repeated measures Anaysis of Variance. (Cohen, J. and Cohen, P. *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences.* NJ: Erlbaum, L. 1983).

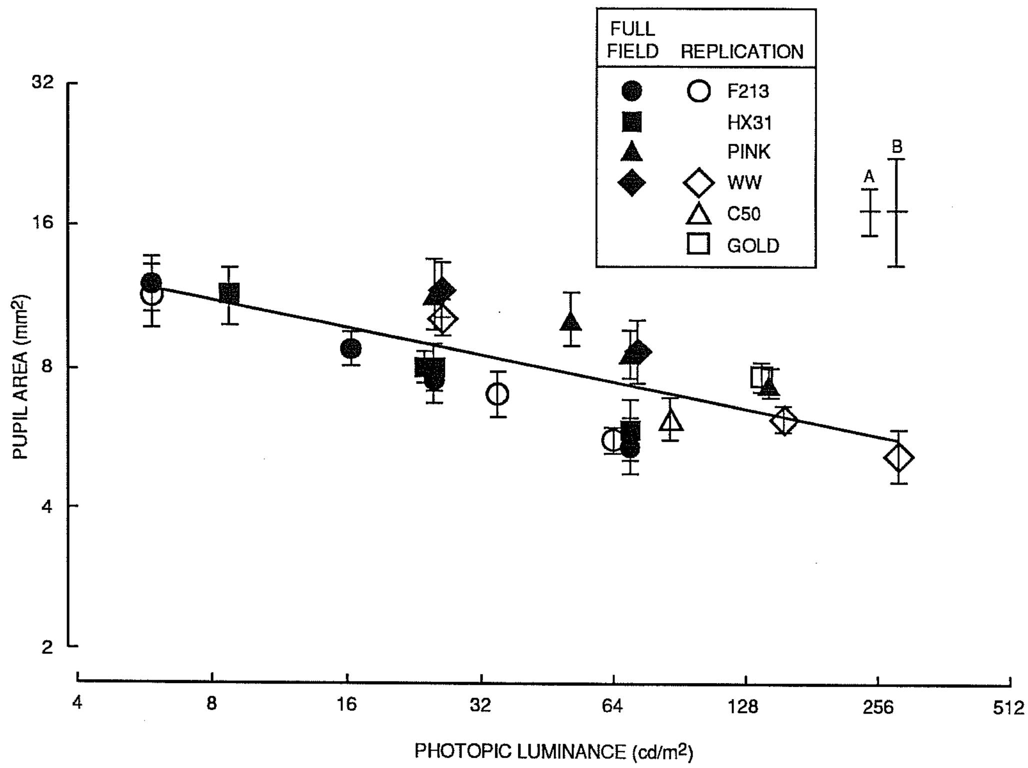

Figure 1. The natural log of the mean subject pupil area as a function of photopic luminance.

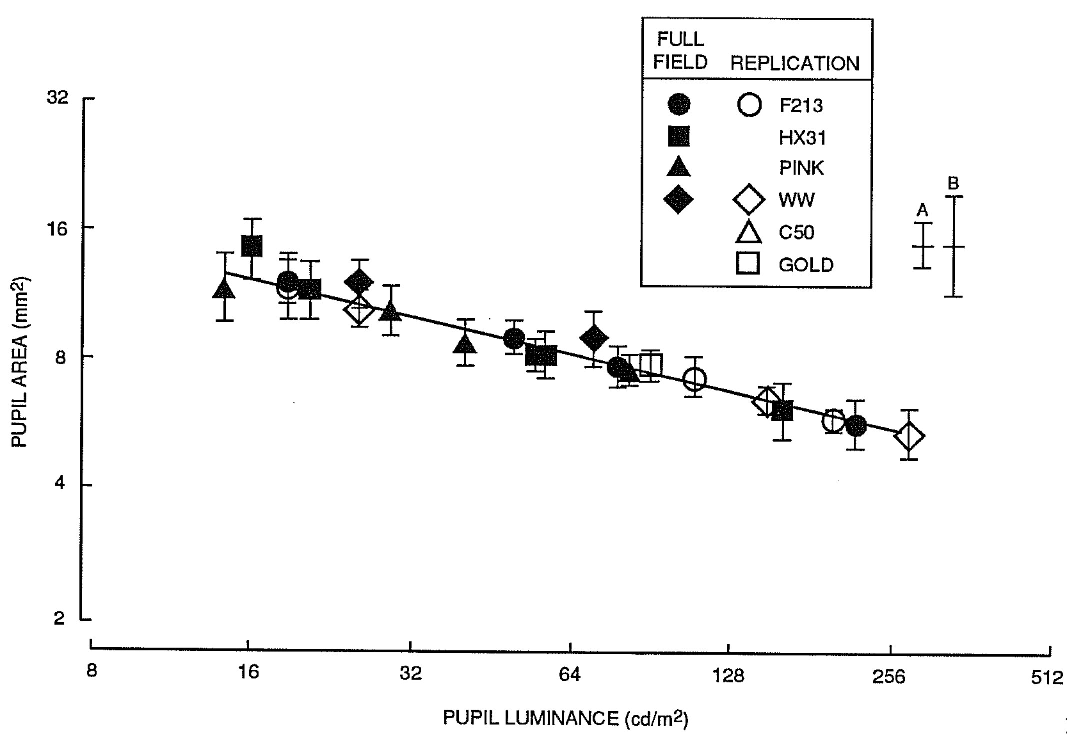

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Figure 2. The same data as Figure 1, but with the abscissa replaced by pupil luminance (eq. 2).

To accomplish our studies on visual performance, we have introduced the lighting engineers equivalent of the vision scientists' Maxwellian view system. In the traditional Maxwellian new system, which is usually monocular, pupil size is defined by a fixed mechanical or optical aperture with field size, surround and task luminances controlled by various optical constructions. In our system subjects are studied binocularly while seated in a whitish room with pupil size controlled by indirect surround lighting conditions (spectrum or luminance level) while task lighting, white in color, is separately controlled by using a CRT or a light box. Surround lighting and task lighting are kept separate by providing the task apparatus with a black tube that allows subjects to view the task, but prevents surround lighting from falling on the task surface. Our studies generally compare performance under 2 different surround spectra that in turn, cause 2 different pupil sizes.

We have completed 10 separate studies, each involving typically about 12 different subjects. The studies are listed in Table 1. These studies differ according to whether the task is orientation of a quasi Landolt C or a word reading accuracy task; the pupil size is controlled by varying surround spectrum with fixed photopic luminance or instead fixed spectrum and varying surround luminance level; task luminance is also varied; the surround field size is varied to affect disability glare; subjects are young, old; or specifically correctly refracted; surround lighting is provided by a standard commercially available lamp; and whether subjects are correctly refracted while under mydriasis. The studies are carried out in the same room as the pupil spectral response study. Figures 3 and 4 show the set-up for the Landolt C and the word reading tasks respectively. Note that the task device is surrounded by either a black curtain or a black immediate background in order to reduce the effects of disability glare on task performance.

TABLE 1: Visual Performance Studies

EXPERIMENT TITLE	PUBLISHED?	No. Subs	LIGHTING CONDITIONS	NOTES
Spectral Control - subject's ages 21 to 37 years	Yes	12	**Surround** : Red/Pink combination compared to F213 at 69 pcd/m^2 **Task** : Landolt C on CRT at 13.2 pcd/m^2	Landolt C acuity improved in F213 condition.
Luminance control - subject's ages 21 to 45 years	Yes	12	**Surround** : F213 at 3.5 and 53 pcd/m^2 **Task** : Landolt C on CRT at 13.2 pcd/m^2	Landolt C acuity improved in higher surround condition.
Spectrum control and task luminance change - subjects's ages 18 to 45 years.	Yes	12	**Surround** :red-pink conbination vs. F213 at 53 pcd/m^2 **Task** : Landolt C luminance range 13 to 73 pcd/m^2	F213 yields better performance at all task luminances
Elderly Study - Subects ages 61 to 66 years	Yes	7	**Surround** : Red/Pink combination compared to F213 at 69 pcd/m^2 **Task** : Landolt C on CRT at 13.2 pcd/m^2	Landolt C acuity improved in F213 condition.
GE lamp study	No	15	**Surround** : F213, ww, JP297B, JP90D at 53 pcd/m^2 **Task** : Landolt C at 13.2 pcd/m^2	Performance increased with scotopic content (smaller pupils).
Luminance Control Replication	No	15	**Surround** : F213 at 5 and 50 pcd/m^2 **Task** : Landolt C on CRT at 13.2 pcd/m^2	Replication of Luminance Control Study results.
WW Reading Chart Study	No	9	**Surround** : WW at 5 & 50 pcd/m^2, **Task** : Reading words of varying size letters - Luminance at 20,50 & 80 pcd/m^2	No significant pupil size change seen. No performance change.
F213 Word Reading Accuracy Study - subject's ages 23 to 59 years	In Progress	9	**Surround** : F213 at 5 & 50 pcd/m^2, **Task** : luminance at 20, 50, & 80 pcd/m^2	Performance increase with higher surround (smaller pupils).
Daylight lamp Study - subject's ages 23 to 59 years	No	12	**Surround** : Chroma-50 at 5, 10, 50, & 100 pcd/m^2 **Task** : Landolt C at 13.2 pcd/m^2	Performance increase with higher surround. First study to show performance change with standard white light commercial lamp.
Controlled Refraction Study - subject's ages 21 to 35 years	In Progress	12	**Surround** : F213 & Pink at 50 pcd/m^2 **Task** : Landolt C at 13.2 pcd/m^2	Performance improved with F213 (smaller pupils) 0.50 D blur increases effect. No effect of surround spectrum - induced color eliminated as mechanism in other studies.

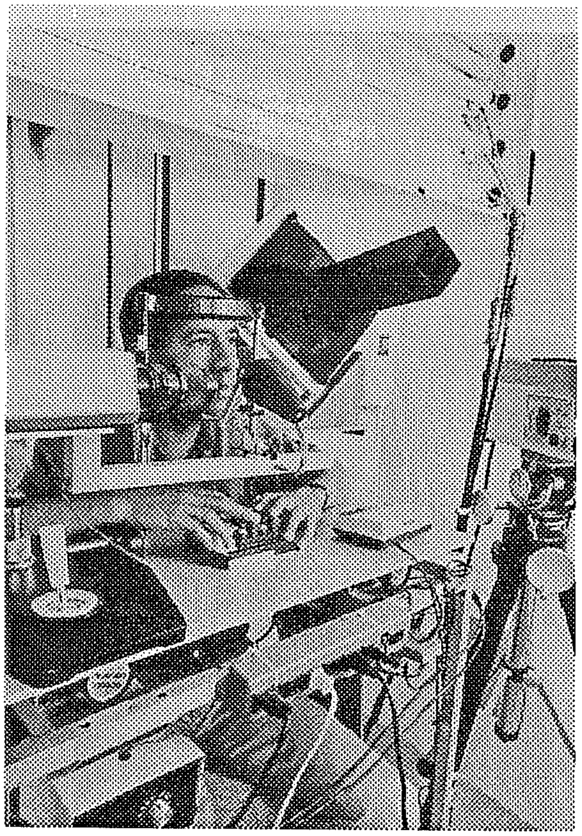
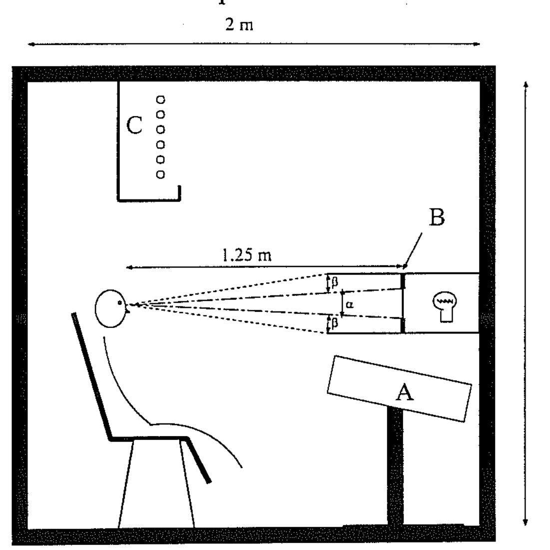


Figure 3. Photograph of the test room showing the set-up for the Landolt C recognition study (LBL photo ZBB 916-4499).

3.1 Landolt C recognition

For the studies where the task is the determination of the orientation of a Landolt C, the gap is approximately rectangular subtending a visual angle of 2 min. with the task located at a distance of 2.4 m. The 'C' is presented on a white background which in this study has the fixed luminance of 13.2 cd/m^2. Further details, including procedures for measuring task contrast, are given in Berman et. al.[13] The 'C' orientations are at 45° with respect to the horizontal to reduce effect of longitudinal astigmatism. In these studies the contrast of the 'C' is varied and threshold contrast for each subject is determined by fitting the data with probability of seeing functions.

Data was collected in blocks, which included 20 presentations of the 'C' for each of four levels of task contrast, with orientation of the 'C' and task contrast randomly varying over presentations within a block, while surround illumination and task background luminance was held fixed within the block. The sequence of luminances and surrounds was randomly varied across subjects. The subjects' task was to press one of the four buttons on a keypad indicating the orientation of the Landolt C just presented (forced choice). Each 200 millisecond 'C' presentation was preceded by a 2.5 second pupil size measurement. The pupil size measurement prior to the next presentation was initiated one second after the subject responded to the previous presentation. Six blocks of data were collected for each of the two respective surround lighting conditions. As mentioned above, the order of lighting conditions was randomized for each subject and at each lighting change the subject was adapted for at least 2.5 minutes before starting testing. A short training period with relatively high values of the 'C' contrast allowed subjects to become familiar with the test procedures.



A- Remote Pupillometer/Eyetracker
B- Back Illuminated Task
C- Flourescent Fixture

α: Angle subtended by illuminated portion of task.
8.1 deg vertical
6.4 deg horizontal

β: Angle subtended by black border and surround shield
4.8 deg vertical
6.9 deg horizontal

Figure 4. Locations of equipment used in the Reading chart study. The reading task luminance was kept independent from the surround luminance by means of the "surround shield" which subtends approximately 20 degrees.

Some sample results of these studies are discussed below for both young adult and elderly subjects. When varying the spectrum of the surround lighting was used as the means for controlling pupil size (but at a fixed level of photopic luminance of 53 cd/m^2) pupils were smaller for the scotopically enhanced spectrum (F213 lamp S/P=4.31) compared to the scotopically deficient spectrum (Red/Pink lamp combination S/P=0.24). For young adult subjects in the Landolt C study, mean pupil areas went from 11.1 ± (0.6 s.e.) mm^2 to 18.2 ± (1.1 s.e.) mm^2. For the elderly subjects (61-66 years of age) mean pupil area went from 9.9 ± (1.1 s.e.) mm^2 to 13.7 mm^2 ± (1.1 s.e.) mm^2.

Although the pupil size changes obtained in this study of elderly subjects were about one-half of that occurring the previous study of young adult subjects, the data of Figure 5 shows that the performance changes were comparable. Our elderly subjects had an average pupil diameter decrease of 18% associated with a mean threshold contrast decrease from 35% to 24%. The young adults had, on average, twice the change in pupil diameter and mean threshold contrast decreased from 27% to 18%.

For the scotopically enhanced surround lighting the average pupil area for our elderly subjects was about 28% smaller than for the scotopically deficient surround lighting, so task retinal illumination was concomitantly decreased by 28%. Yet, performance was significantly better despite the decreased retinal illuminance. This result is consistent with the hypothesis that the improvements obtained in visual performance by increasing light levels for older people[14,15] is primarily due to the decrease in pupil size resulting from increased ambient luminances, rather than an increase in retinal illuminances.

3.2 Questions of disability glare

Our data for young adults also allows for testing the alternative hypothesis that disability glare caused by the surround lighting is the mechanism responsible for their difference in performance. Because pupil size is smaller under the scotopically enhanced surround (F213), the photopic retinal veil caused by light scatter in the eye should be less than the veil produced by the larger pupil occurring under the scotopically deficient surround (red/pink). In the young adult experiments, in addition to the data presented above which was gathered at a task background luminance of 13.2 cd/m^2, the study was also carried out at task background luminance's of

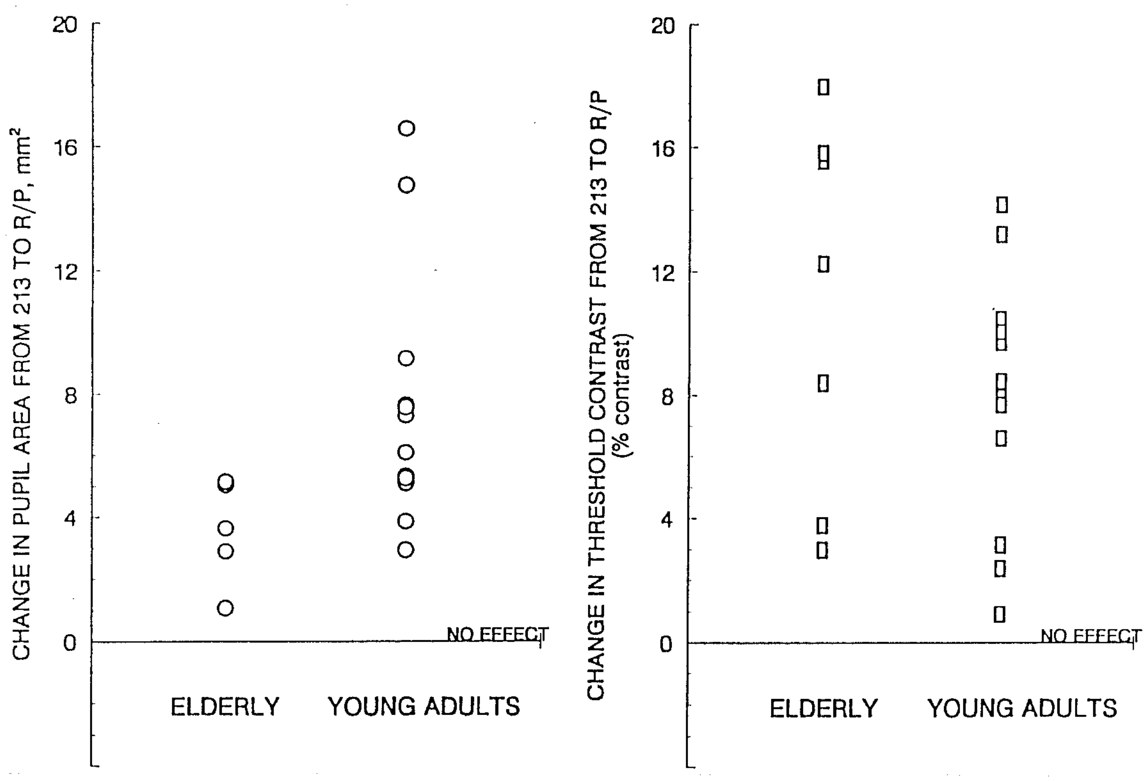


Figure 5. Pupil size and performance differences for the young adults and elderly subjects when the surround lighting was changed from the scotopically enhanced F213 spectrum to the scotopically deficient Pink spectrum, both providing a photopic surround luminance of 53 cd/m^2. Note that the task lighting is fixed at 13 cd/m^2 and with this change in the surround spectrum, all subjects showed increases in pupil size and elevated threshold contrasts.

27.7, 47.0, and 73.4 cd/m^2, with the surround illuminant conditions unchanged. Since the veil resulting from the surround illuminants was of constant luminance, the effect of this veiling glare should decrease as the task background luminance increases. From the expressions of Vos[16] on disability glare, we can calculate that the veil due to light scatter would have resulted in reductions in contrast that went from 2.1% at 73.4 cd/m^2 task background luminance to 12.0% at 13.2 cd/m^2 task background luminance. If these effects were responsible for the performance differences in the experiment, then those performance differences should have been larger under conditions of lower task background luminance; however, there was no significant interaction effect between surround illuminant and task background luminance ($F_{3,7}=0.83$, $p=0.52$). For disability glare effects to be at work in these experiments, one would have to postulate that such effects are specific to the elderly where we did not vary task luminance. Nevertheless, even without specific knowledge of the mechanisms the scotopically enhanced lighting does provide a higher level of performance compared to the scotopically deficient lighting for our elderly subjects.

The absolute performance of the elderly subjects for a given surround condition is generally poorer than that of the young adults of our previous study, i.e., threshold contrasts are higher. On the other hand, we speculate that the reason why the <u>change</u> in performance of the elderly and young adult subjects are comparable despite a smaller pupil size change, is that our elderly subjects may have an increased amount of ocular aberrations, as is known to occur with senescence of the eye.[17] Thus, it is possible that small changes in the pupil size of the elderly can have a large effect on their performance of difficult visual tasks. For the parameters and conditions of our study, our results suggest that both neural degradation and dioptric factors affect Landolt C recognition (although this may not be the case if the size of the task is sufficiently small).[17]

3.3 Eliminating the induced color hypothesis

There is yet another alternative hypothesis that needs to be considered and which is <u>not</u> based on pupil size changes as the mechanism responsible for our observed performance effects. Under this hypothesis the performance changes are due to a spectrally dependent interaction between the periphery and fovea of the eye (induced color) and that this interaction causes better performance when the surround has the blue/green spectrum rather than the pinkish spectrum. This kind of interaction has not been reported in the literature and would be of interest if true.

To test the hypothesis of a performance effect due to induced color we studied 12 new subjects (3 females and 9 males ages 21 to 35) under conditions of mydriasis. Each subject was carefully refracted by an optometrist under both conditions of natural pupil state and under mydriasis. The study then examined whether spectrally controlled pupil size affected Landolt C performance with and without mydriasis. If subjects showed a performance benefit with smaller pupils, but did not show any changes in performance in the cyclopleged condition then the induced color hypothesis can be eliminated. Furthermore, if subjects show a performance benefit with natural pupils even though they have been refracted, we can hypothesize that the pupil size performance effects should be present in the general population.

The experimental conditions were similar to the previous studies except that a different pupilometer was used (ASL 4250) which eliminated the previous potentially fatiguing requirement that subjects perform the study with their head supported in a chin rest. In addition, we also studied performance under conditions of slight blur by adding a lens of 0.5 DS to the subjects refractive state.

The study used a range of contrasts (4, 6, 10, 25, 40, 63, 80%) with 20 'C' presentations repeated 3 times at each of four contrasts. These were chosen so that they covered the dominant range of performance variation for a particular subject. Presentations were randomized over contrast, 'C' orientation, repetition and surround lighting. Mydriasis was obtained by 2 drops of 1% tropicamide in each eye and repeated once during the study session.

The data were analyzed within a repeated measures Analysis of Variance framework. All subjects went through all of the procedures, which constituted a 2x2x2x4 repeated measures design. The factors were: dilation (normal vs. mydriasis), blur (normal vs. +0.50 DS blur), surround lighting (50 pcd/m^2 F213 vs. 50 pcd/m^2 pink), and task contrast (4 levels). Since the range of task contrasts was different for different subjects and sometimes needed to be adjusted within a subject between conditions (to accommodate for poorer performance with blur and/or dilation), the data were unbalanced and could not be analyzed using standard ANOVA procedures. The data were analyzed using the P5V procedure of the BMD statistical package.[18] This procedure uses Maximum Likelihood estimation with structured covariance matrices to solve the unbalanced design. Prior to statistical analysis, for each subject, the average pupil size and the Landolt C task accuracy (i.e., percent correct) were computed for each contrast level for each of the eight experimental conditions.

Task contrast was then converted to effective task contrast by adjusting for the effective veil luminance produced by surround light scattered in the eye[16] (about 4% of surround luminance) and by the small amount of light getting down the tube (1%). In BMDP5V, the unbalanced factor (effective task contrast) was analyzed as a covariate which varied across the repeated measures. Both linear and quadratic components of the effect of effective task contrast on Landolt C accuracy was estimated.

The results of the analysis showed under conditions of normal (light responsive) pupils that subject pupils were significantly smaller under the scotopically enhanced lighting, 11.6mm^2 ± 1.1 mm^2 (s.e.) compared to 20.6mm^2 ± 2.0 mm^2 (s.e.) under the scotopically deficient lighting. Subjects performed better under the scotopically enhanced lighting with an improvement of 8.9% ± 1.2% (s.e.) over the scotopically deficient lighting (χ^2[1 df] = 56.6, p << 0.00001). Under conditions of mydriasis there were highly significant linear and quadratic effects of contrast on performance. However, there was no effect of surround light spectrum on performance (χ^2[1 df] = 1.97, p = 0.16. Furthermore, under the blurred mydriasis condition there was a highly significant reduction in performance of 18.6% ± 1.4% (s.e.) p << 0.00001 and again, there was no effect on performance of surround spectrum (χ^2[1df]=1.97, p=0.16). Figure 6 shows the mean results for the four conditions (normal pupils no blur, normal pupils blurred, dilated pupils no blur and dilated pupils blurred).

Since there was no effect on performance in the dilated (and fixed) pupil condition associated with the change in surround spectrum, we conclude that the performance effects observed in our previous studies is not due to the induced color effect. In addition, we showed that performance was decreased when blur was added in the dilated pupil condition showing our measures were sensitive to effects that cause performance decrements.

3.4 Controlled subject refractions

In addition, for normal pupils we found that subjects even though correctly refracted, showed a performance benefit for the smaller pupil condition. Similarly to the pervious study of Landolt C performance, a 35% reduction in effective task retinal illuminance (191 to 125 T) (Stiles-Crawford effect included) caused by the smaller pupil is accompanied by a 9% improvement in performance. This result for correctly refracted subjects further supports our claim that the entire population should, on average, have better acuity with smaller pupils as would result by the general application of scotopically enhanced lighting.

4. WORD READING

In the Landolt C orientation studies discussed above, task luminance was fixed while task contrast was varied and pupil size was controlled by adjusting the spectrum of the surround illumination. We next extend the studies to the case where the task is reading of random words that are presented at fixed high contrast (black print on white background), but with varying letter size. Word reading is a complex resolution task which is representative of tasks in typical workplace environments. In this study letter size is the crucial task variable. When size is reduced approaching threshold values, word reading ability will diminish significantly from the near perfect accuracy obtained at larger letter values. In this sensitive domain, we can again investigate the trade off between retinal illuminance and pupil size.

This study uses procedures similar to our previous studies but chronologically was carried out before the mydriasis study was undertaken. At that stage in our research we wanted to avoid the possibility of a confounding condition due to the induced color effect. Instead of adjusting the surround spectra, we chose to affect pupil size by varying the level of surround luminance using a single illuminant. To accomplish this we chose the F213 fluorescent lamp as the illuminant for the surround with a high and low luminance of 50 cd/m^2 and 5 cd/m^2 to achieve 2 pupil sizes. The choice of this protocol is disadvantageous to the smaller pupil condition because both the veiling glare luminance and the small light leakage that succeeds in traveling down the viewing tube are proportional to the surround luminance. Thus, these potentially confounding light contributions will be an order of magnitude larger under the high surround luminance condition. For the conditions of this study about 1.8 cd/m^2 of luminance finds its way down the tube and the calculated veiling glare luminance due to light scatter in the eye[16] has a value of 2.5 cd/m^2.

4.1 Protocols

Nine subjects (7 females and 2 males) ages from 23 to 59 years participated in this study and were obtained by advertising in a local newspaper. Each subject was studied under 6 different lighting conditions: 2 levels of surround luminance (5 and 50 cd/m^2) and 3 levels of task luminance (20, 50, 80 cd/m^2). The task material was 24 unique reading charts size 22 cm by 28 cm, each having 10 lines of words with 6 words per line, printed in a fixed point

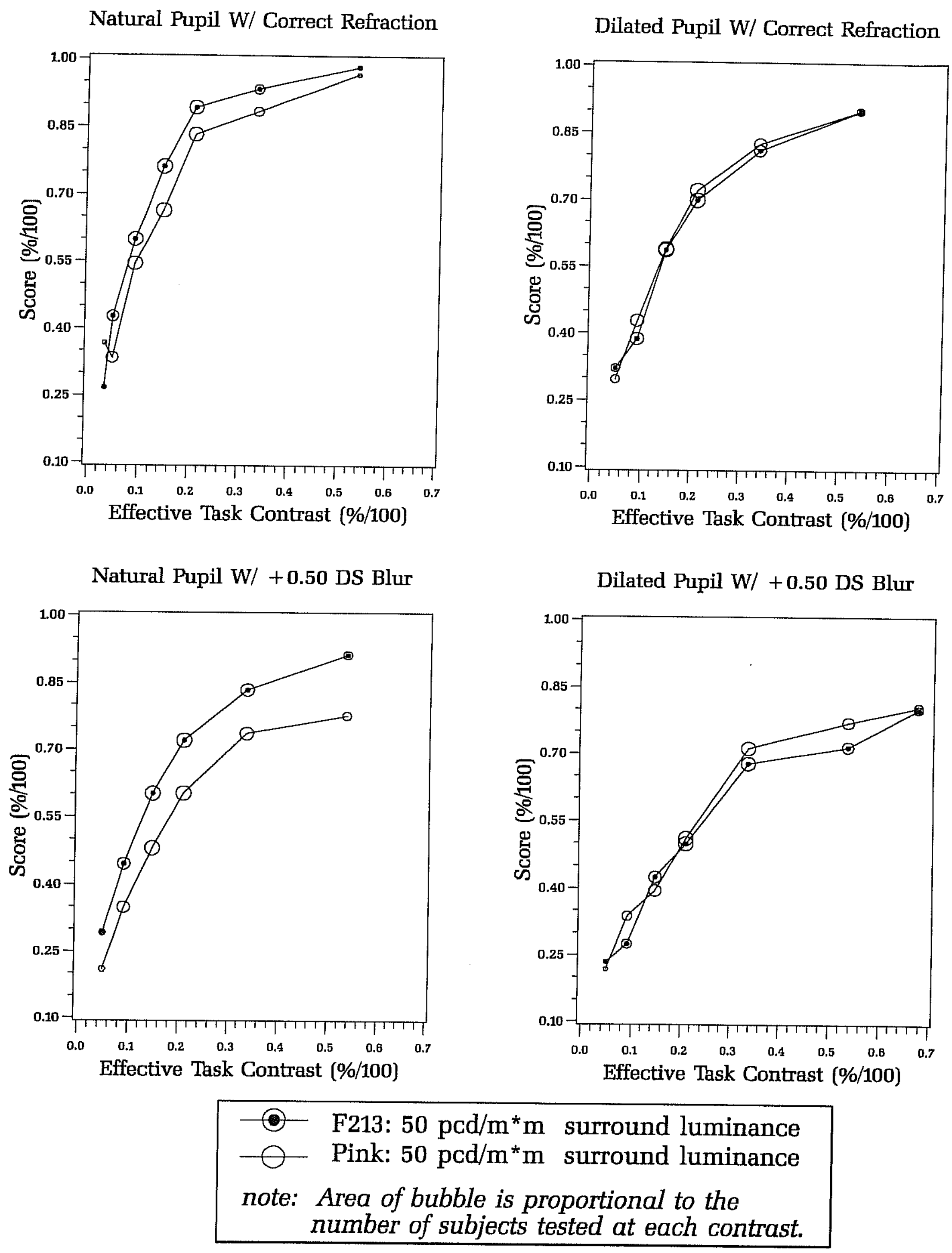


Figure 6. Mean percent correct for recognition of orientation of a Landolt C as a function of its contrast (white background and gray C) for natural and dilated pupils with and without a +0.50 DS blur. F213 Illumination is the scotopically enhanced surround and Pink is the scotopically deficient surround. Task background luminance was kept constant at 13.3 cd/mm^2.

size - Times-Roman font. The letter size decreased from line to line. For the subject distance of 1.25 m the acuity ranges were from top to bottom 20/25 (6/7.5 or 0.10 log MAR) to 20/8.9 (6/2.67 or -0.35 log MAR). The charts were printed on clear transparencies at 2540 dpi resolution.

The charts were mounted in a box backlit with incandescent lighting. Diffusing and IR filters were placed between the incandescent lamps and the charts, luminance variation over the backlit area was less than 10%. The remaining perimeter of the viewed task surface was a black border of vertical thickness 2.5 cm and horizontal thickness 6 cm. Just as in the Landolt C studies, the task was protected from the surround lighting by a black shield extending outward from the task about 40 cm (see Fig. 4).

Pupil size was measured during performance using the ASL pupilometer which allowed subjects to sit relaxed in a comfortable chair. A period of 2 minutes was allowed for adaptation to each of the six conditions and subjects read 3 to 4 charts per condition.

The subjects' reading of the charts was recorded on a micro cassette recorder. After all the charts were read, the audio tape was reviewed by a different experimenter than the one who conducted the subject to determine the number of words read correctly on each chart. The experimenter or scorer had no knowledge of what the condition under which each chart was read. A word was considered correctly read if two thirds of the letters were identified.

4.2 Data analysis

Prior to statistical analysis, for each subject, pupil size and reading accuracy data were averaged across charts for each of the six task lighting by surround lighting conditions. Each dependent variable (average pupil size and average number of words read per chart) was then analyzed using a repeated measures Analysis of Variance design with six repeated measures (two surround luminances by three task background luminances) per subject. As noted above, light scatter in the eye and leakage of surround lighting onto the task resulted in different task background luminances at the two surround lighting levels (i.e., the design had unbalanced rather than fully crossed experimental factors). This necessitated the use of the BMDP-5V program[18] which uses structured covariance matrices to analyze unbalanced repeated measures Analysis of Variance designs. Using this BMDP5V program, the unbalanced factors (the task luminances) were analyzed as covariates which varied across the repeated measures. Both linear and quadratic effects of task background luminance on the dependent variables were estimated. This fitting is the maximum allowable model independent statistical characterization of these effects given that they were only measured at three levels of task background luminance.

The reading accuracy data were also analyzed a second time as a function of surround luminance and task retinal illuminance (i.e., effective trolands). For each subject, for each of the surround lighting by task background lighting conditions, effective task retinal illuminance was computed from that subjects average pupil size and specific task background luminances, taking into account the Stiles-Crawford effect. The task background luminance values used in this latter computation were adjusted for light scatter in the eye and for leakage of surround lighting onto the task.

4.3 Pupil size

The pupil size data as a function of surround and task background luminance are presented in Figure 7.

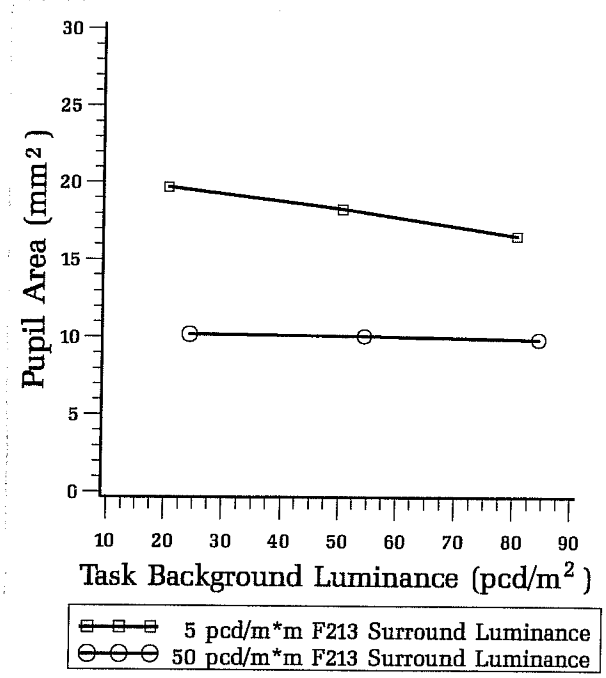


Figure 7. Mean pupil area for the two levels of surround luminance as a function of task background (reading chart) luminance.

There was a large pupil size increase as surround luminance was decreased from 50 to 5 pcd/m^2 (χ^2 [1 df] = 47.71, $p < 0.0001$), with the average subject's pupil area increasing on average by 8.07 mm^2 (s.e. = 0.79 mm^2) from the mean value 10.02 mm^2 in the high surround condition for the average level of task background luminance. There was a strong 'trend' toward a significant interaction effect on pupil size of task background luminance by surround luminance (χ^2 [1 df] = 3.41, p = 0.065). This interaction was due to the pupil size effect of task background luminance being present only under the low surround luminance conditions (χ^2[1 df] = 1.40, p = .24), and (χ^2 [1 df] = 42.37, p < .0001) for the task background effect at high and low surround luminance conditions, respectively).

4.4 Reading accuracy as a function of task background luminance

The reading score data as a function of task background luminance and surround luminance are displayed in Figure 8. The score data shows a nearly linear increase in accuracy of about 2 words as the task background luminance increases from 20 cd/m^2 to 50 cd/m^2 followed by a leveling off as the task background luminance reaches 80 cd/m^2. There was a non-significant interaction effect between task background luminance (both linear and quadratic components) and surround luminance on reading score (p-values were > 0.41 for both linear and quadratic task background luminance by surround luminance effects). This means that the fits of reading score as a function of task background luminance were essentially parallel for the two levels of surround luminance. There were highly significant linear and quadratic effects of task background luminance on reading score (χ^2 [1 df] = 28.26 and 14.34), respectively, both p's < 0.0001).

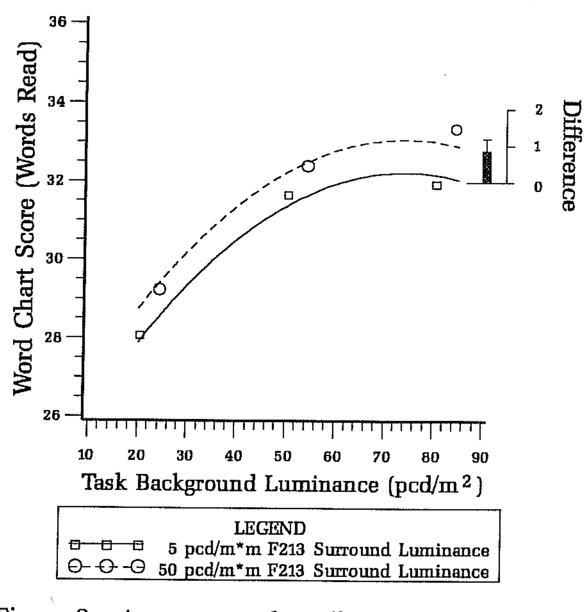


Figure 8. Average word reading score for the two surround luminances as a function of task background (reading chart) luminance.

There was also a significant effect of surround luminance on reading score (χ^2 [1 df] = 6.07, p = 0.014), with the average subject reading 0.85 more words (s.e. = 0.35 words) in the high surround condition for a given level of task background luminance.

4.5 Reading accuracy as a function of retinal illuminance

The reading score data as a function of effective task retinal illuminance and surround luminance are displayed in Figure 9. The score data shows behavior similar to the case above, but exhibits a larger difference between the two surround conditions. There was a non-significant interaction between effective retinal illuminance (both linear and quadratic components) and surround luminance on reading score (p-values were > 0.64 for both linear and quadratic task background luminance by surround luminance effects). This means that the plots of reading score as a function of retinal illuminance were essentially parallel for the two levels of surround luminance. There were highly significant linear and quadratic effects of effective retinal illuminance on reading score (χ^2 [1 df] = 50.16 and 21.80, respectively, both p's < 0.0001). There was also a highly significant effect of surround luminance on reading score (χ^2 [1 df] = 30.49, p < 0.0001), with the average subject reading 2.00 more words (s.e. = 0.36 words) in the high surround condition (smaller pupil) for a given level of retinal illuminance.

4.6 Discussion

In this study, pupil size was controlled by varying the luminance level of the surround which covered the visual field beyond the central 21°. There was a highly significant improvement in reading accuracy for smaller pupils. This effect of smaller pupils on reading accuracy more than compensated for the decrease in retinal illuminance caused by the smaller pupil. Thus, increased retinal luminance was not associated with improved acuity.

Our hypothesis is that the improvement in reading accuracy when the surround luminance increases (while task luminance is fixed) is due to the observed decreases in subjects' pupil sizes. This improvement occurs in spite of two confounding factors previously mentioned above that combine to make the task at the higher surround luminance condition (smaller pupils) more difficult than in the low surround condition. First, there is a small fraction (3.6%) of the surround light that manages to incur on the task and second, there is the indirect illuminance on the retina caused by surround light scatter in the optical media. Both of these effects are 10 times larger for the high surround condition (as they are proportional to the surround luminance) and add together to reduce the effective contrast of the task for that condition.

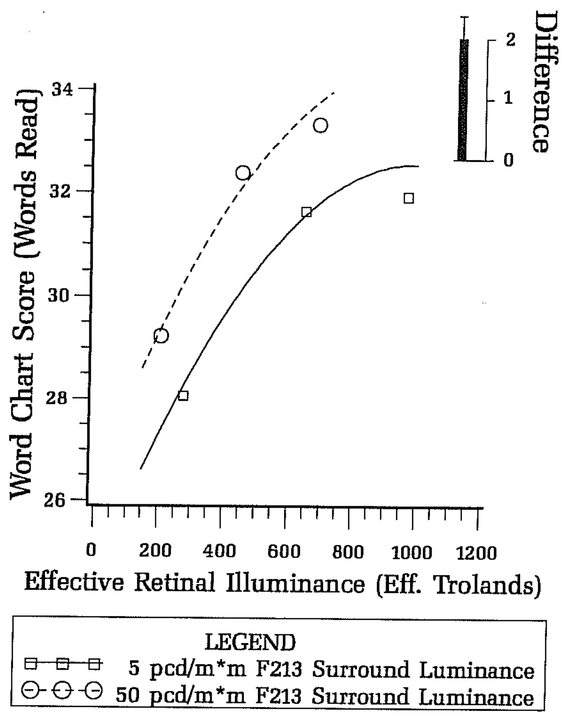


Figure 9. Average word reading score for the two surround luminances as a function of effective task retinal illuminance (task background luminance * pupil area).

For example, at the lowest task background luminance of 20 cd/m2, task contrast at the high surround condition is reduced from near 100% to 82%. When the task size reaches criticality such reductions in contrast can increase task difficulty reducing the pupil size benefit. Nonetheless, our results showed that the pupil size effect was sufficiently robust to yield a significant difference in reading accuracy even in the context of these countervailing effects. Were we able to control or eliminate these countervailing effects, the pupil size effect on reading accuracy would most likely be larger in degree than the average value of about 1-word obtained here.

This study demonstrates again, similarly to our previous studies of Landolt C recognition discussed above, that the increased task retinal illuminance associated with the larger pupil does not compensate for the direct pupil size effect on visual performance. For the larger pupil, task retinal illuminances were typically 80% higher than for the smaller pupil, but yielded less reading accuracy. We interpret these results that once a sufficient level of light flux is available to the eye, i.e., typical of interior light levels, optical system aberrations play a more dominant role in the ultimate determination of visual acuity than retinal illuminance.

Several past studies[19,20,21] have shown improvements in acuity associated with increases in task luminance as we also have found, e.g., Figure 9. However, in those studies pupil size was not controlled and the observed acuity improvements could have been partly a result of the decreasing pupil size caused by increasing the task luminance which was also the surround luminance. Some data on pupil size was provided in those studies and in all three of these studies, the results showed a decrease in pupil size associated with the increasing task/surround luminance. In view of our results here we believe it is likely that the increases in acuity of these studies were due, at least in part, to the pupil size effect and were not solely a result of increased retinal illuminance. More recent studies by other researchers using new approaches have also shown that pupil size can affect grating acuity and that it is improved with smaller pupils.[22]

For each of the two pupil size conditions, our results (Figure 9) are qualitatively similar to those of Shlaer[23] who demonstrates, for two subjects with fixed 2 mm diameter artificial pupils, a slight rise in high contrast Landolt C acuity with increasing luminance over the same range of luminances as in our task reading study. An unanswered and interesting question arises as to whether the observed performance difference in score for the two pupil sizes as reported here (Fig. 9) would continue at higher task luminances.

Shlaer[23] also measured grating acuity for fixed 2 mm artificial pupils and found that it saturated in the range of luminances of our study. As mentioned above, we did not extend the range of task luminances in the present study to examine possible saturation of reading accuracy with increased task luminance. It is possible that the continued slight increase in Landolt C acuity (but not in grating acuity) observed by Schlaer mentioned in the previous paragraph is due to a task artifact. The orientation of the 'C' can be established without actually recognizing the gap per se, but instead by observing a contrast variation over the 'C' surface due to the presence of the gap. With such a shift in criterion the "real" task size may not be simply defined by the gap and apparent recognition can be accomplished by a sensitivity to a luminance contrast gradient threshold rather than an actual recognition of the gap detail. Thus, the question as to whether performance and/or acuity saturates at different values depending on pupil size needs further investigation.

5. CONCLUSION

The results of this word reading study and our studies of Landolt C recognition demonstrate that for values of task luminance typical of building interior conditions, acuity and contrast sensitivity are improved with smaller pupils. These results are obtained for subjects ranging in age from 20 to 70 years and with at least 20/20 vision. Since the spectral response of pupil size is dominated by scotopic sensitivity, specification of light levels solely by use of the photopic response leaves the lighting practitioner with an inadequate predictor of visual function. This inadequacy is further exacerbated by the results of our study on perceived brightness which show a major scotopic contribution to brightness perception in full field conditions.[24] Taken together these studies imply that conventional photometry needs to be supplemented. The resultant enhanced photometry will allow lighting practice to more adequately include the effects of lighting on human vision in realistic conditions. Such an enlarged concept of photometry will lead to the most energy efficient lighting economy.

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